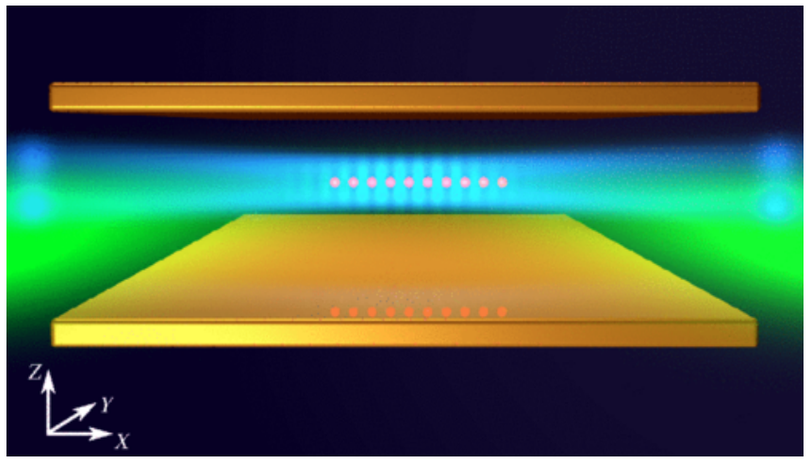
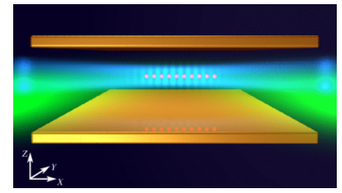
Towards realisation of long-lived chains of circular Rydberg atoms for quantum simulation



Ankul Prajapati

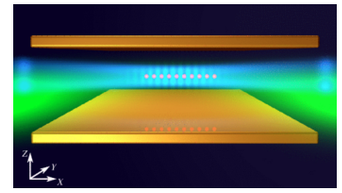
Laboratoire Kastler Brossel, École Normale Supérieure, Paris, France

Outline

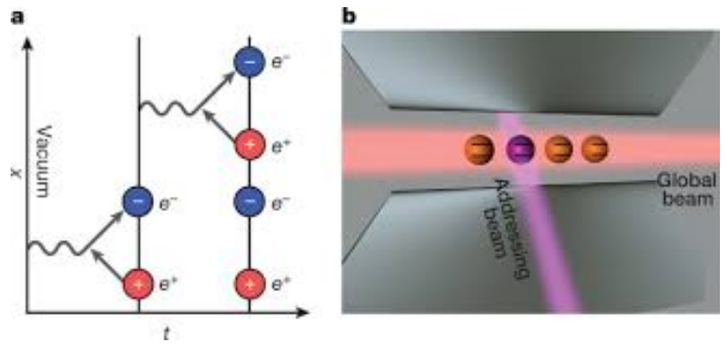


- State of the art in context of HEP
- Circular Rydberg (cRy) atoms
- Inhibition of spontaneous emission in cRy
- cRy preparation
- cRy atoms trapping
- Experimental setup
- Summary

State-of-the-art for gauge theories

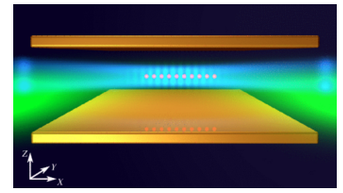


Few-ion quantum simulation

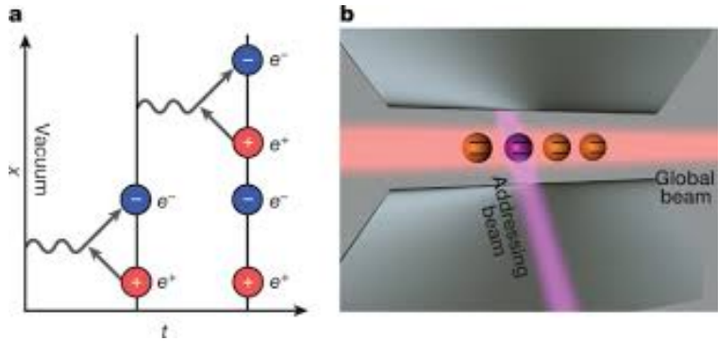


E. A. Martinez *et al.* Nature **534**, 516-519 (2016)
N. H. Nguyen et al. PRX Quantum **3**, 020324 (2022)

State-of-the-art for gauge theories



Few-ion quantum simulation



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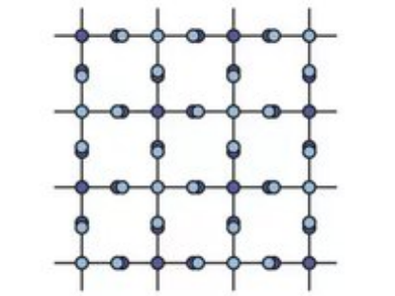
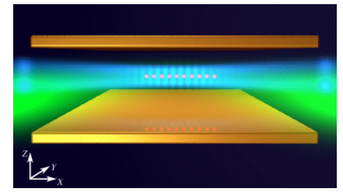
Cold atoms in optical lattice

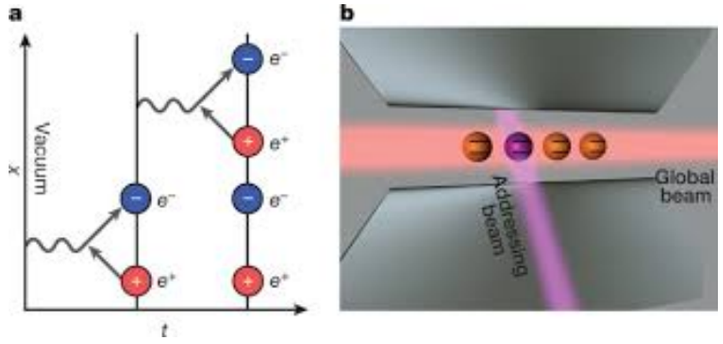


B. Yang *et al.* Nature **587**, 392-396 (2020); Z.-Y. Zhou *et al.*, Science **377**, 311 (2022);
Halimeh, J.C. *et al. Nat. Phys.* (2025)

State-of-the-art for gauge theories



Few-ion quantum simulation



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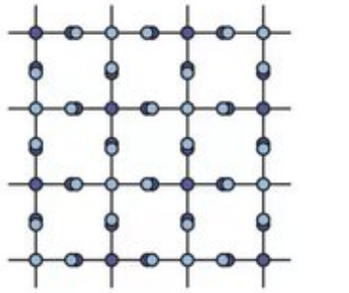
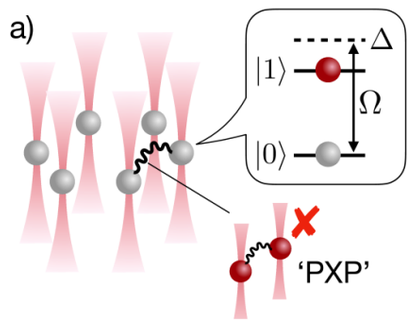


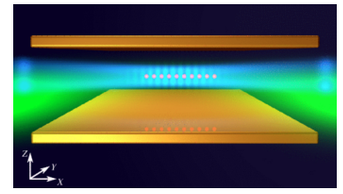
B. Yang *et al.* Nature **587**, 392-396 (2020); Z.-Y. Zhou *et al.*, Science **377**, 311 (2022);
Halimeh, J.C. *et al. Nat. Phys.* (2025)

Trapped low l Rydberg atoms

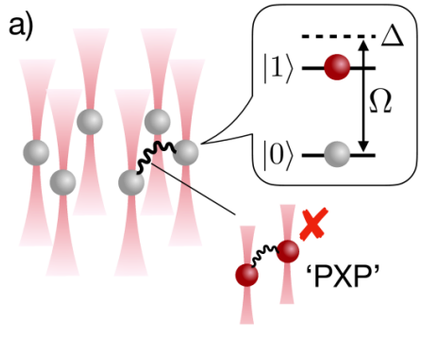


H. Bernien et al. Nature 551, 579 (2017);
F. M. Surace et al. Phys. Rev. X 10, 021041 (2020)
arXiv:2408.02733v1 (2024)

State-of-the-art: Rydberg atoms

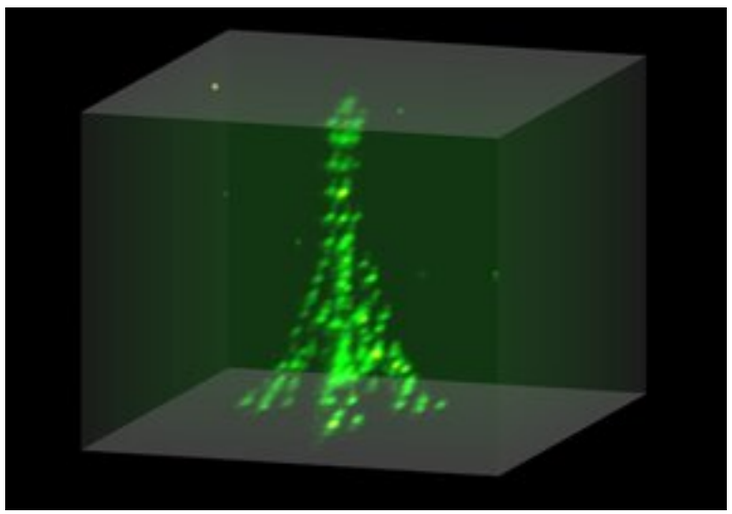


Trapped low l Rydberg atoms



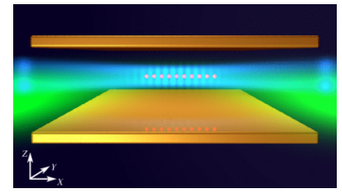
H. Bernien et al. Nature 551, 579 (2017);
F. M. Surace et al. Phys. Rev. X 10, 021041 (2020)
arXiv:2408.02733v1 (2024)

- ☑ Rydberg states: $n \gg 1$, low angular momentum
- ☑ Giant size and **sensitive to electric field**.
- ☑ **Strong dipole-dipole interactions**
- ☐ Lifetime ≈ 200 μs at 4 K
- ☐ Shorter evolution times for larger arrays
- ☐ Optical transitions and BBR at 300K



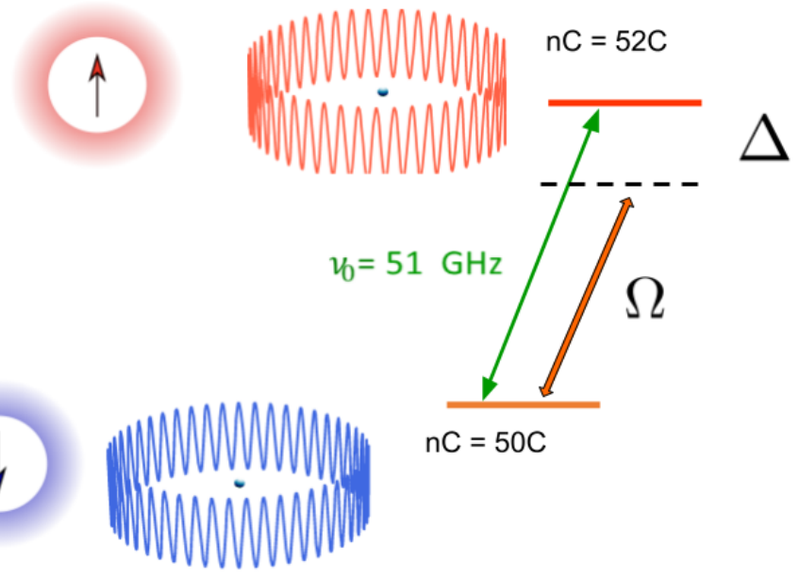
Nature 561, 79 (2018)

State-of-the-art: cRy atoms



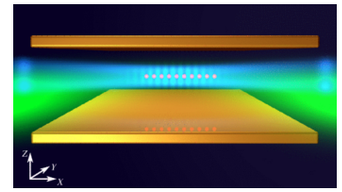
Circuler Rydberg states: $n \gg 1$, max angular & magnetic momentum

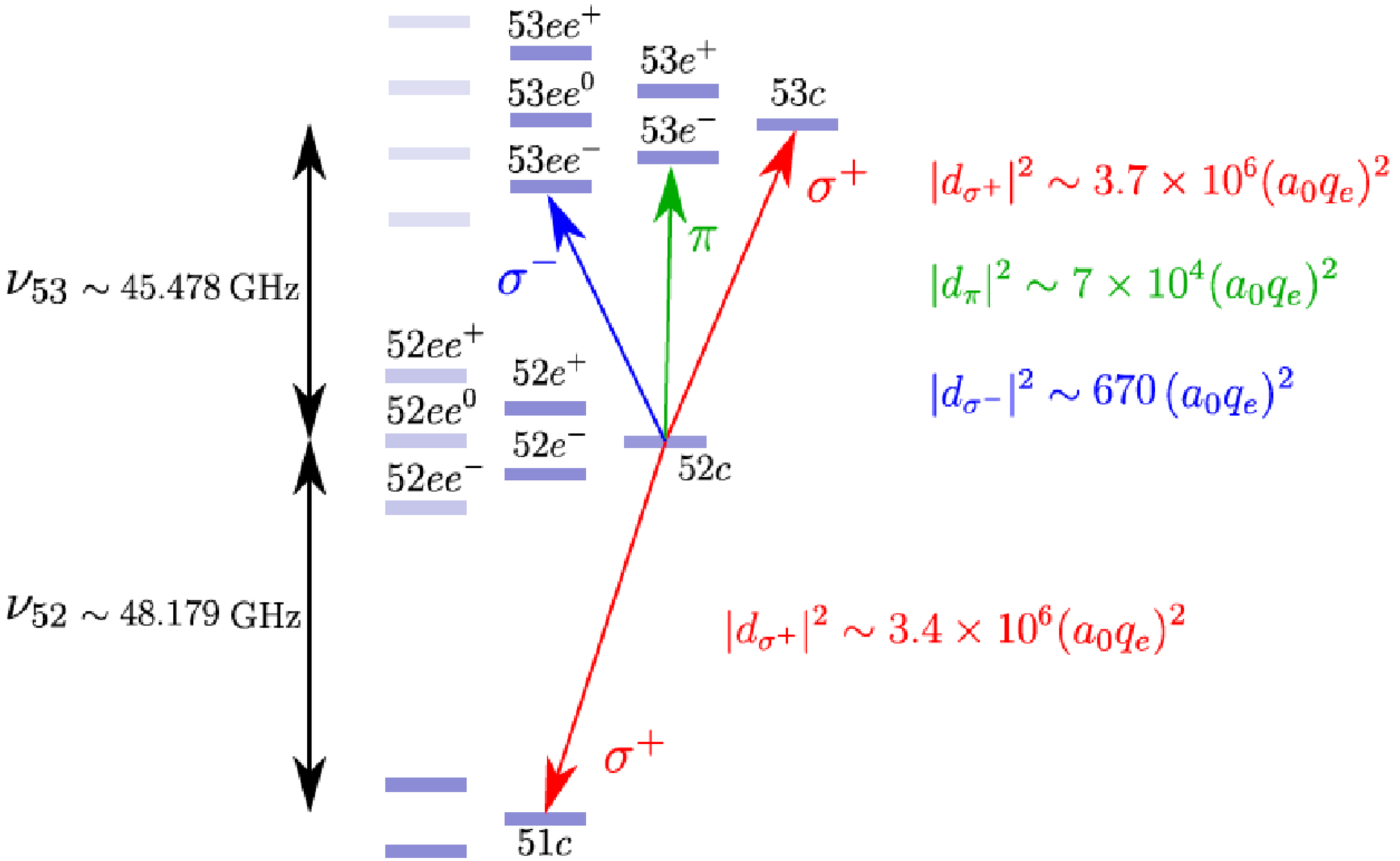
- ☑ **Strong interactions!**
- ☑ Good coupling to microwave fields.
- ☑ **Long-lived states:** 52C ⇒ $\tau \approx 30$ ms at 0.4 K.
- ☑ **Longer evolution times for larger arrays**
- ☐ **Only one spontaneous decay channel**
- ☐ **Sensitive to BBR at 300K**



Phys. Rev. X 8, 011032 (2018)

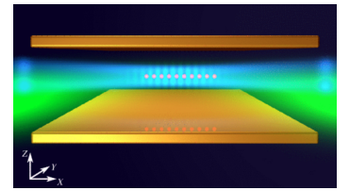
Circular Rydberg atoms: Loss channels



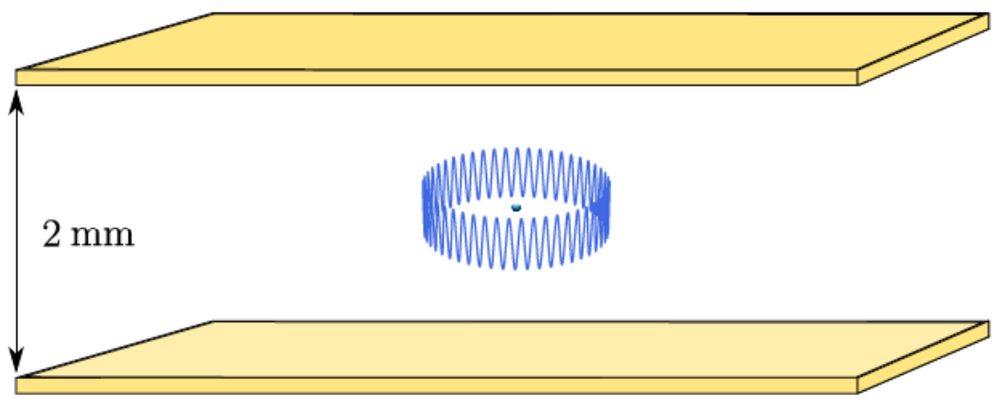


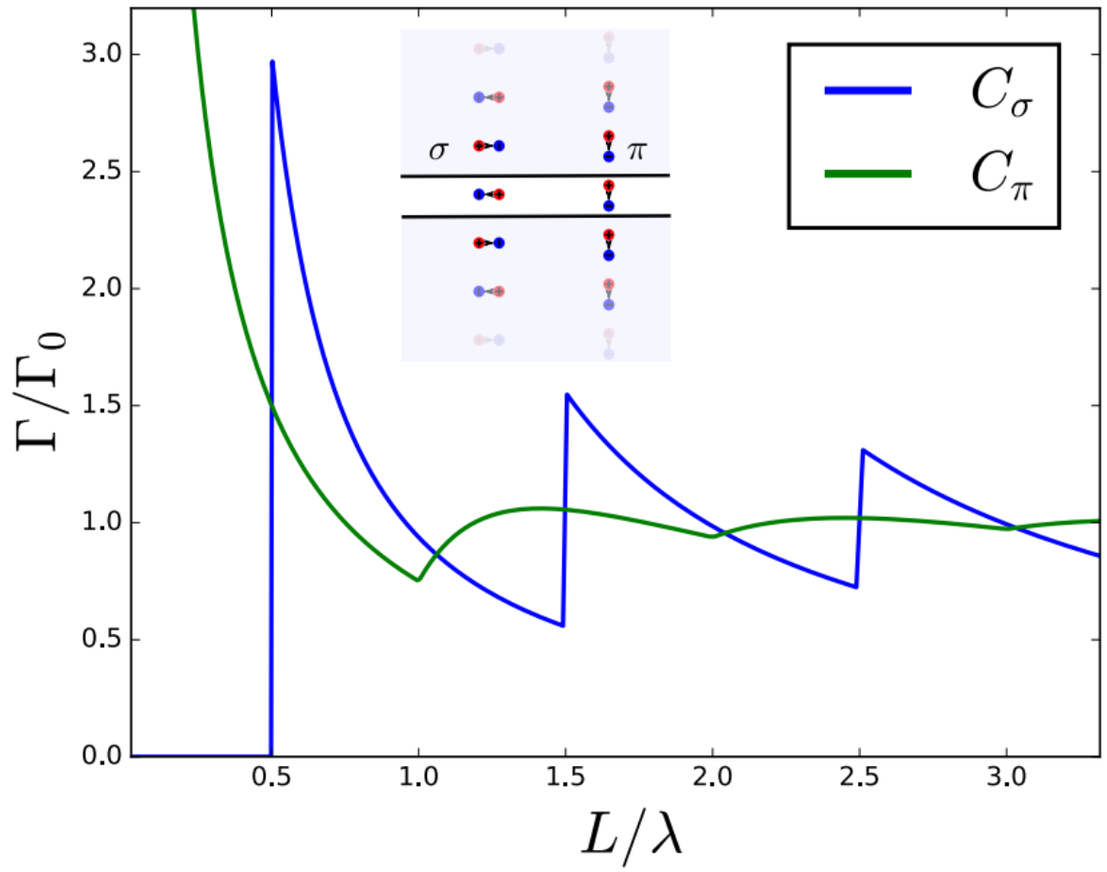
Phys. Rev. Lett. 47, 233

Circular Rydberg atoms: Inhibition



Inhibition plane capacitor plates

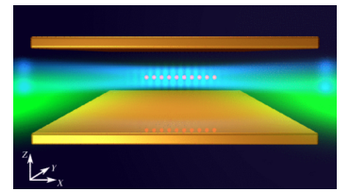




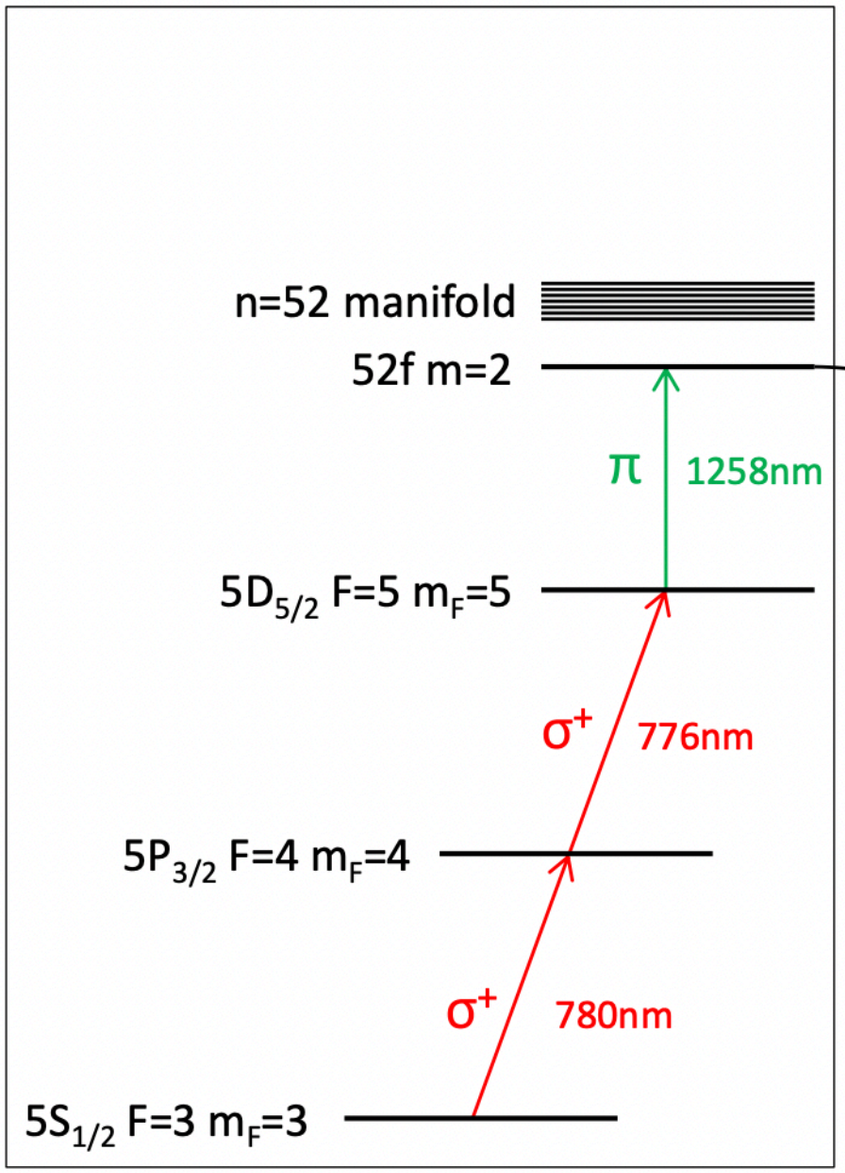
☑ **Expected cRy state $52C$ lifetime of ~ 40 s**

Phys. Rev. Lett. 47, 233

Circular Rydberg atoms* preparation

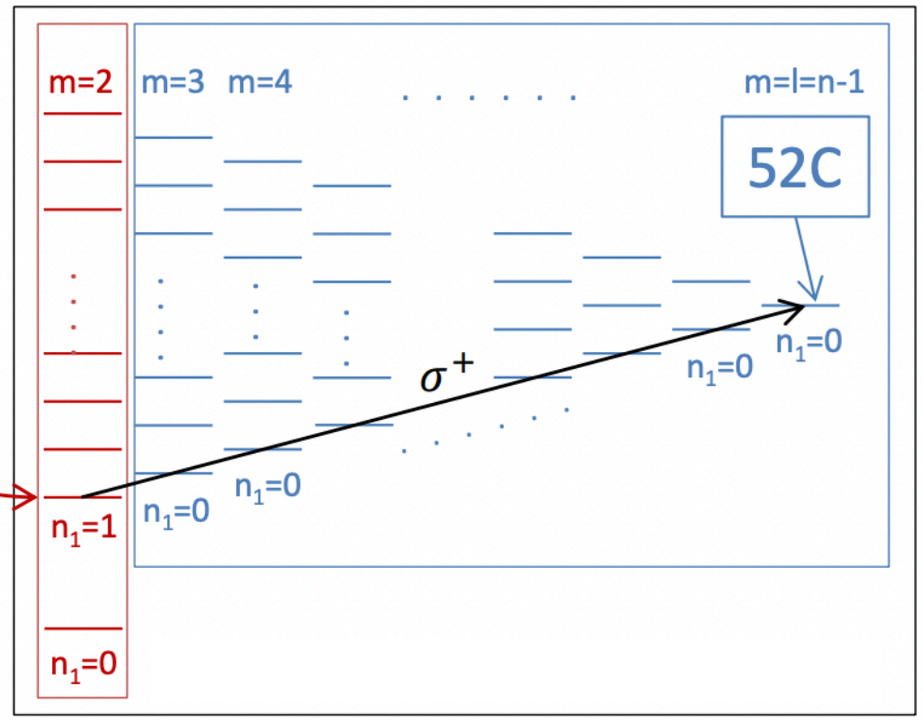


Optical excitation to the Rydberg state



Stark switching

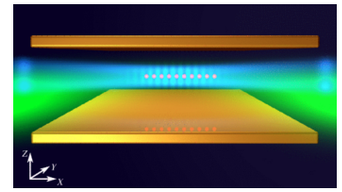
Adiabatic passage to the circular Rydberg state



*Rubidium 85

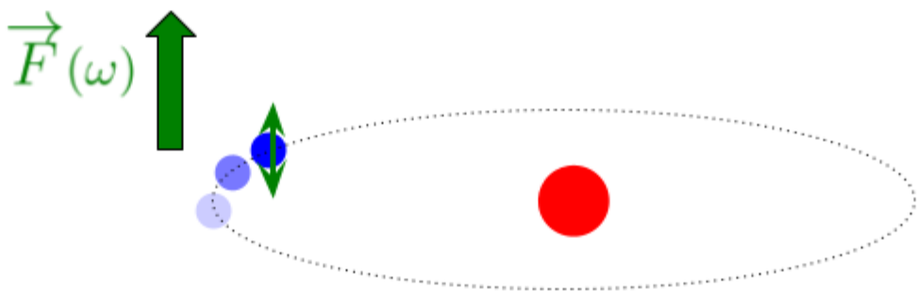
Phys. Rev. Lett. 130, 023202 (2023)

Circular Rydberg atoms: Trapping



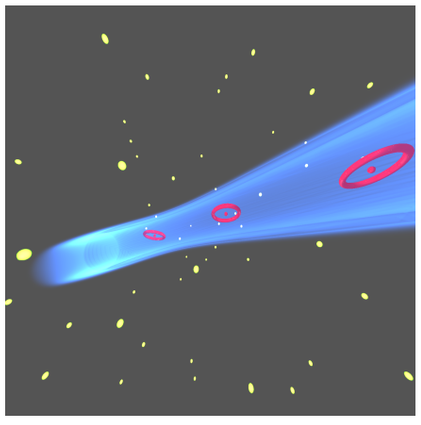
Ponderomotive (repulsive) potential:

S K Dutta., Phys. Rev. Lett. 85, 5551



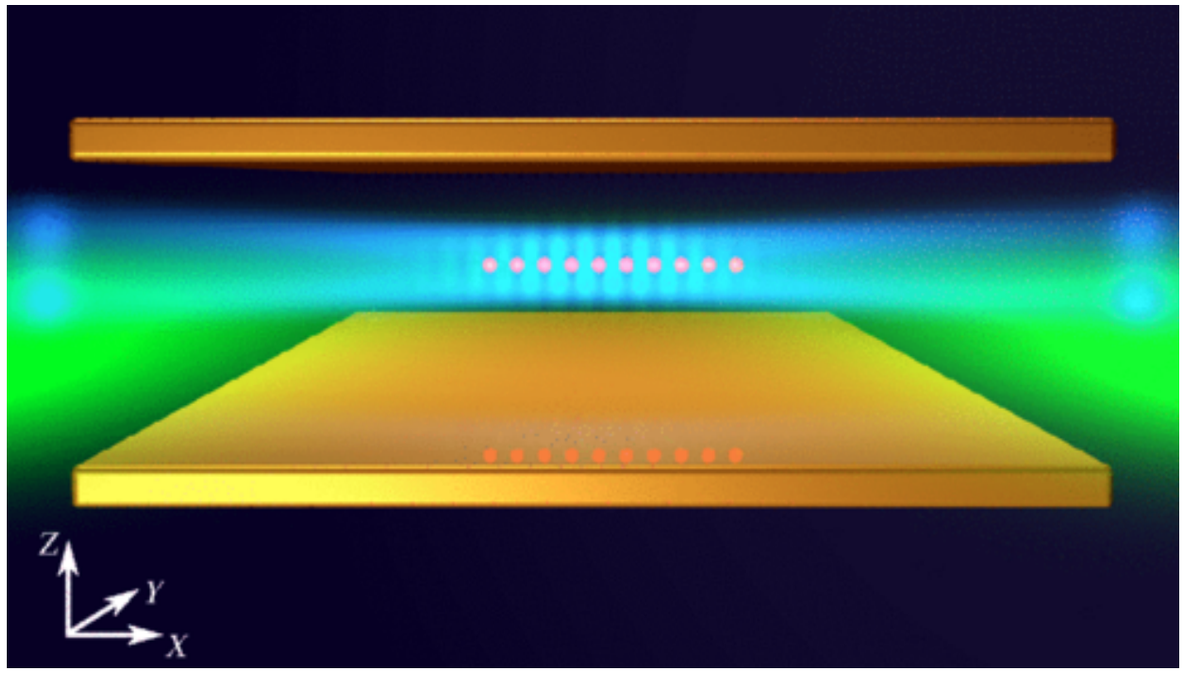
$$\mathcal{E} = \frac{e^2}{2m_e\varepsilon_0 c\,\omega_L^2} I$$

- Almost-free Rydberg electron repelled by light field
- Requires intensity minima: Hollow Laguerre-Gauss beam
- Circular Rydberg states: no photo-ionisation



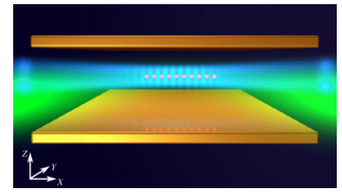
Phys. Rev. Lett. 124, 123201

Future quantum simulator!

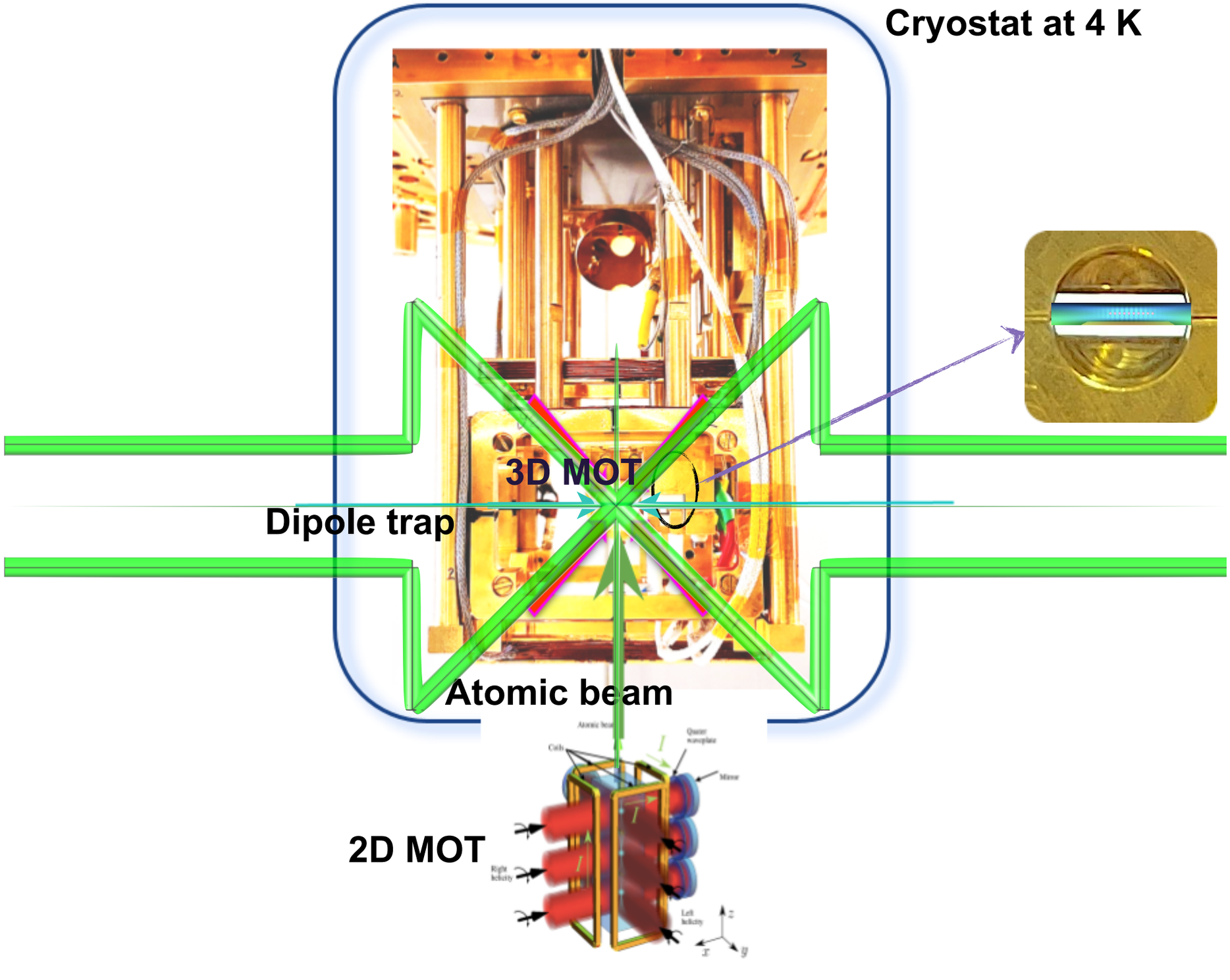


Long lived chains of circular Rydberg atoms for quantum simulation!

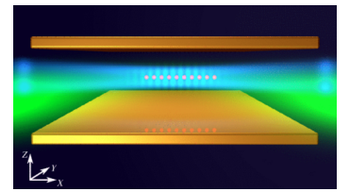
Experimental setup

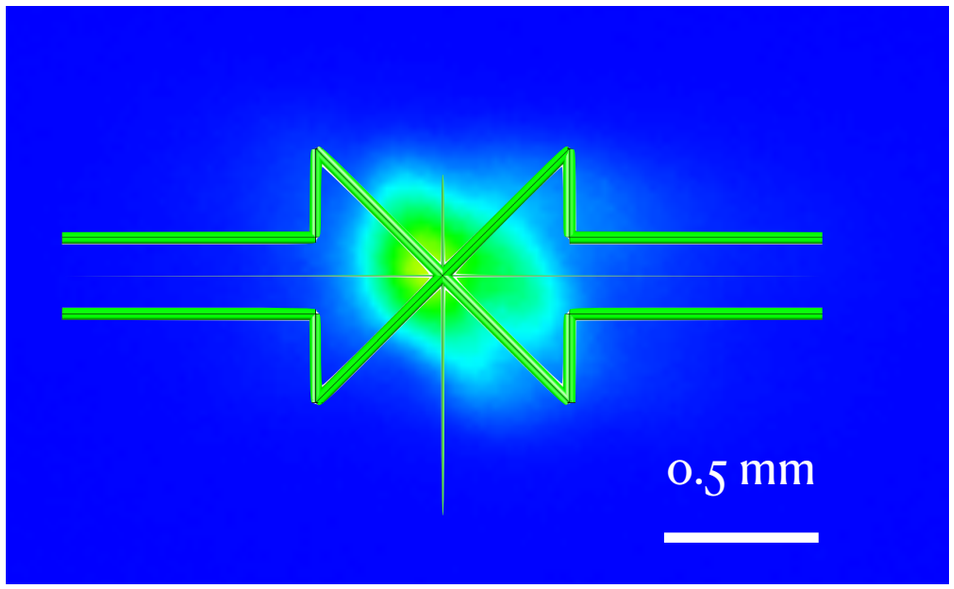


Cryostat at 4 K



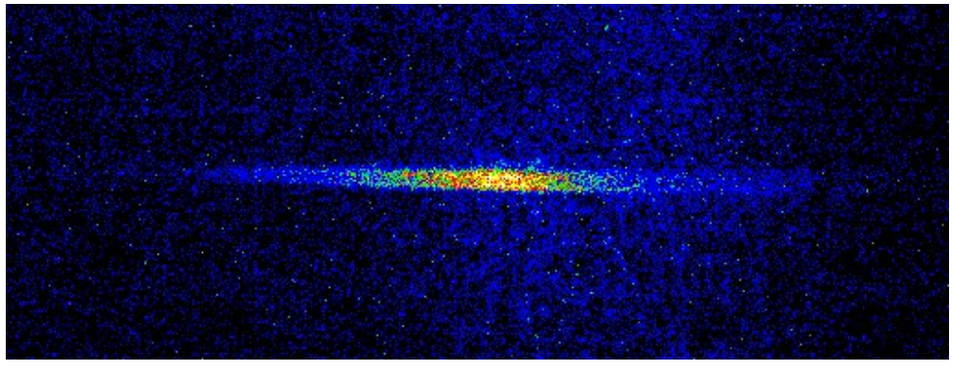
Current status of the experiment





3D MOT:

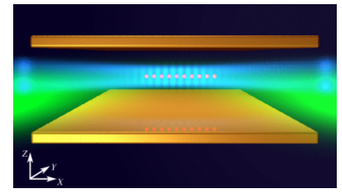
- **Stable MOT in cryogenic environment**
- MOT Temperature ~ $40\mu K$
- Molasses at ~ $10\mu K$



Dipole trap:

- Good optical access
- Waist control using tunable lenses
- Characterisation in progress!

Summary



Quantum simulation with circular Rydberg atoms

- Spin dynamics under the XX or XXZ Hamiltonians
- Explore HEP problems
- Exploit the large Rydberg multiplicity
  - ✳ Simulation of large-spin Heisenberg Hamiltonians
  - ✳ Simulation of quantum field theories

    A. Kruckenhauser… P. Zoller, Quantum Sc. And Tech. 8, 015020 (2022)

Thank you!

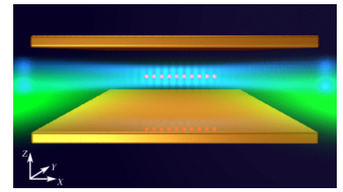
For more info: https://www.lkb.upmc.fr/cqed/

Would love to connect!

Thank you!

For more info: https://www.lkb.upmc.fr/cqed/

XXZ Hamiltonian



Ising interaction

Spin exchange interaction

Longitudinal B field

Transverse B field

$$H/h = J_z \sum_j \sigma_j^z \sigma_{j+1}^z + J \sum_j \left(\sigma_j^x \sigma_{j+1}^x + \sigma_j^y \sigma_{j+1}^y \right) + \frac{\Delta}{2} \sum_j \sigma_j^z + \frac{\Omega}{2} \sum_j \sigma_j^x$$